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ON DYNAMIC STABILITY OF NUCLEAR POWER
PLANTS

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Nuclear power plants intended to operate in remote, difficult-to-reach areas of the country have to possess not only high safety but also definite dynamic characteristics.

A low power plant, operating out of the power system and supplying a small number of consumers, can be exposed to considerable external load changes. Practically it must be stable and withstand the full external load removing and increase. It should be taken into account that from the economic point of view, pump and control system drives and another plant electric equipment is advisable to be power supplied from the same turbogenerator as well as external consumers. In addition, the plant control system must be the simpliest, not requiring highly skilled specialists to operate it.

Therefore it seems to be necessary to use to the maximum self-regulating properties of power systems.

The object of the present paper was to study peculiarities and the character of transients of nuclear power plants, at which a steam generator had a boiling water free level. As studies have shown, the dynamic properties of nuclear plants of this type meet the requirements of "small-sized nuclear power plants".

Steam generators with boiling water free level usually have relatively large secondary circuit water capacity. Transients in power plants with such a steam generator, dependent on changes of secondary circuit parameters (steam extraction, feed water

flow rate and its temperature) run with great time delay, slowly as compared to the reactor transients. Because of this the latter may be considered to be quasi-static and studying the system dynamic stability as a whole the reactor should be considered only in a quasi-static asymptotic approximation. It means that the influence of terms of high orders in the reactor transfer function is neglected. The whole system may turn out to be aperiodically stable even at oscillatory stability of the reactor. As far as high oscillation frequencies, which can be caused in the reactor by different reasons, are filtered at a steam generator and in other primary circuit units great enough and does not pass to reactor input, the system proves to be "unclosed" over high frequencies. The closed system stability problem can be reduced to the dynamic stability study of the reactor at these frequencies and of the closed system, in which the reactor is represented in a quasi-stationary approximation.

While writing down the system of the dynamics equations we have taken a series of simplifying assumption, validity of which is evident enough. The main of them are as follows:

a) Primary circuit coolant flow rate is constant.
b) Steam extraction to the turbine is directly proportional to the load.
c) Feed water supply depends on the change of steam flow rate to the turbine and is carried out through an aperiodic network.
d) One group of delayed neutrons was considered in the equations of kinetics.
e) Feed water subcooling was taken into account in the total steam generator heat balance.
f) The final velocity of upward steam flow in the boiling zone was neglected, that is, boiling water level change because of the void steam content change was ignored.
g) Saturation temperature – pressure dependence is linear.
h) Heat-transfer coefficients are constant. For the reactor it is the consequence of the assumption of the coolant flow rate permanency. It is true for a steam generator if the heat-transfer coefficient is slightly dependent on heat flux.

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i) Reactivity changes are small and the equations of kinetics
may be linearized.

j) Transport delays in pipings were approximate by an aperiodic
network.

The solution of the system of the reactor dynamics equations
can be expressed with these rather general approximations as the
transfer function $\alpha(s)$ which describes coolant temperature
changes at the reactor outlet with temperature fluctuations at
the reactor inlet. Let this function be conventionally "the reac-
tor transfer function" though it usually denotes the function
which is characteristic of power changes versus reactivity chan-
ges:

$$\alpha(s) = -\frac{\tilde{\vartheta}_{outlet}}{\tilde{\vartheta}_{inlet}} = -\frac{F_i(s)}{F_0(s)} \tag{1}$$

where

$$F_0(s) = s\left(s + T_\mu^p\right)\left(s + T_{II}^p + 0.5 T_\perp^p\right) - 0.5 s T_\mu^p T_\perp^p - \alpha_e^* A_0 T_\perp \left(s + T_0\right)$$

$$F_i(s) = s\left(s + T_\mu^p\right)\left(T_{II}^p - 0.5 T_\perp^p\right) + 0.5 s T_\mu^p T_\perp^p + \alpha_i^* A_0 T_\perp \left(s + T_0\right) \tag{2}$$

The functions $\alpha_e^*(s)$ and $\alpha_i^*(s)$ are correspondingly equal.

$$\alpha_e^*(s) = \alpha_e + \beta_0 s$$

$$\alpha_e = 0.5 \alpha_T \bar{\theta}_0 \left\{ 1 + \left(1 + 2 \frac{T_{II}^p}{T_\perp^p}\right) \frac{\beta_T}{\alpha_T} \right\}$$

$$\beta_0 = \frac{\bar{\theta}_0}{T_\perp^p} \tag{3}$$

$$\alpha_i^*(s) = \alpha_i = 0.5 \alpha_T \bar{\theta}_0 \left\{ 1 + \left(1 - 2 \frac{T_{II}^p}{T_\perp^p}\right) \frac{\beta_T}{\alpha_T} \right\}$$

The reactivity changes can be represented as a function of
reactor inlet and outlet coolant temperature:

$$\tilde{\rho}_T = \alpha_i^*(s) \tilde{\vartheta}_{inlet} + \alpha_e^*(s) \tilde{\vartheta}_{outlet} \tag{4}$$

It is seen from equations (1) and (2) that the reactor as a
dynamic system has a characteristic equation of the third order.
However, in most cases the function $\alpha(s)$ can be simplified by
neglecting the terms s^3 and s^2 as the heat-transfer coeffi-
cient and the fuel element heat conductivity and hence the
reactor dynamic constants usually are proved to be great enough.

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Besides that, high frequency components in the function of inlet coolant temperature changes in a closed reactor system are negligible.

If the steam generator boiling water level is assumed to be held approximately constant at all transients due to controlled feed water supply and is assumed to be left above the coil levels, then it is easy to get the relation between $\tilde{\vartheta}_{inlet}$ and $\tilde{\vartheta}_{outlet}$ solving steam generator heat transfer equations

$$\tilde{\vartheta}_{inlet} = f(s)\left\{A_1 \tilde{\vartheta}_{outlet} + (s+T_1)\frac{\psi A_2}{T_1}\tilde{p}\right\} \qquad (5)$$

where

$$f(s) = \frac{T^{sg} \cdot T_1 T_2}{(s+T^{sg})(s+T_1)(s+T_2)} \qquad (6)$$

The function $f(s)$ can be considered the transient function of series-connected aperiodic networks. The dynamic coefficients T^{sg}, T_1, T_2 are always positive. Therefore, the steam generator, as a dynamic system, is absolutely stable as to the inlet temperature disturbances and to the secondary circuit pressure.

Introducing effective delay time $\tau^{eff} = \tau_1 + \tau_2 + \tau^{sg}$, the function $f(s)$ can be expressed as an aperiodic network

$$f(s) = \frac{T^{eff}}{s+T^{eff}} \qquad (7)$$

where

$$T^{eff} = \frac{\tau_o}{\tau^{eff}} \qquad (8)$$

In case of a reactor with a control system, it is necessary to introduce the equations of an automatic power regulator into the system of equations of the reactor dynamics. The former can be written down considering possible corrections for the process parameters (pressure, temperature and etc.) in the form

$$\begin{aligned} s\tilde{p}_d &= \mathcal{X}_1\left(\tilde{n} - \tilde{n}_3\right) \\ s\tilde{n}_3 &= \mathcal{X}_2\tilde{n}_3 + \mathcal{X}_3\tilde{P} + 2\left(\mathcal{X}_4 + \mathcal{X}_5 s\right)\tilde{\tilde{\vartheta}} \end{aligned} \qquad (9)$$

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In this case the system reactivity changes at pressure distur-
bances (external load) and at introducing the correction for the
steam pressure power demand can "be decomposed" into two compo-
nents: a "temperature" component $\tilde{\rho}_T$ due to coolant temperature
changes and a "pressure" component $\tilde{\rho}_p$. Also, the third compo-
nent $\tilde{\rho}_d$, characterizing a random uncontrolled reactivity
fluctuations, can be introduced. Thus

$$\tilde{\rho}(s) = \tilde{\rho}_T^{eff}(s) + \tilde{\rho}_p(s) + \tilde{\rho}_d(s) \tag{10}$$

where

$$\tilde{\rho}_T^{eff}(s) = \alpha_i^{eff}(s)\,\tilde{v}_{inlet} + \alpha_e^{eff}(s)\,\tilde{v}_{outlet}$$

$$\tilde{\rho}_p(s) = x_p^{eff}(s)\,\tilde{P}. \tag{11}$$

Then, effective "temperature" coefficients of reactivity
$\left(\alpha_i^*(s) \; ; \; \alpha_e^*(s)\right)$ and an effective "pressure" coefficient
of reactivity can be expressed in terms of reactor process para-
meters and of power regulator parameters as follows:

$$\alpha_i^{eff}(s) = \frac{\alpha_i^*(s-x_2)s - x_1(x_4 + x_5 s)}{(s-x_2)(s^2 - x_1 s - x_1 T_0)}\,S$$

$$\alpha_e^{eff}(s) = \frac{\alpha_e^*(s)(s-x_2)s - x_1(x_4 + x_5 s)}{(s-x_2)(s^2 - x_1 s - x_1 T_0)}\,S \tag{12}$$

$$x_p^{eff}(s) = \frac{x_1 x_2}{(s-x_2)(s^2 - x_1 s - x_1 T_0)}\,S$$

Hence, due to linearity of the system of the dynamics equa-
tions, the other process parameter changes (e.g. $\tilde{v}_{outlet}$, $\tilde{n}$)
also can "be decomposed" formally into "temperature", "pressure"
and "reactivity jump" components.
For example,

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$$\widetilde{\vartheta}_{outlet} = \frac{F_i(s)}{F_0(s)} \widetilde{\vartheta}_{inlet} + \frac{F_\rho(s)}{F_0(s)} \widetilde{p} + \frac{F_j(s)}{F_0(s)} \widetilde{\rho}_j \qquad (13)$$

where $F_0(s)$ and $F_i(s)$ coincide in form with the functions (2) which incorporate the relations (12) instead of α_e^* and α_i^*, but $F_\rho(s)$ and $F_j(s)$ are equal, respectivily:

$$F_\rho(s) = \frac{x_\rho^{eff}(s)}{s}(s+T_0)A_0T_\perp^P = -\frac{x_1 x_3 A_0 T_\perp^P (s+T_0)}{(s-x_2)(s^2-x_1 s-x_1 T_0)}$$

$$F_j(s) = \frac{x_j^{eff}(s)}{s}(s+T_0)A_0T_\perp^P = \frac{A_0 T_\perp^P s(s+T_0)}{(s-x_2)(s^2-x_1 s-x_1 T_0)} \qquad (14)$$

It should be noted that to provide the best quality of the transients the automatic power control systems are designed so that time constants of reactor power setting changes and corrections are turned out to be much greater than a time constant of a neutron power regulator, i.e.

$$|x_1| \gg |x_2, x_3, x_4, x_5|$$

It means, that the rate of a neutron power change is much greater than that of a power setting change, power follows changes of a power demand setting, i.e. $n \approx n_3$ at any time instant. Furthermore, the automatic control rod (AP) insertion rate at autonomous regulator adjustment is usually selected so that a control rod (AP) could overcome the "resistance" of a negative temperature reactivity effect and assure a good quality of reactor power transients. It means that the first addend in the numerator of the expressions for α_i^{eff} and α_e^{eff} in (12) must be much less at all frequencies characteristic of the reactor. Hence, neglecting the influence of the temperature effect, while the automatic control rod (AP) in operation and assuming that AP is adjusted so well that it does not cause systematic disturbances of low frequencies in a closed reactor dynamic system, the following equations can be written down instead of equations (12):

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$$\propto_i^{eff}(s) = \propto_e^{eff}(s) \simeq \frac{\mathscr{X}_4 + \mathscr{X}_5\, s}{(s - \mathscr{X}_2)(s + T_0)}\; s$$

$$\mathscr{X}_p^{eff}(s) \simeq \frac{\mathscr{X}_3}{(s - \mathscr{X}_2)(s + T_0')}\; s$$

$$\mathscr{X}_d^{eff}(s) \simeq \frac{s}{\mathscr{X}_1(s + T_0)} \tag{15}$$

With power automatic control system and with due regard for
equations (15), the functions $F_0(s)$ and $F_I(s)$ take the form:

$$F_o(s) = (s - \mathscr{X}_2)\big[(s + T_M^p)(s + T_{\shortparallel}^p + 0{,}5 T_{\perp}^p) - 0{,}5 T_M^p T_{\perp}^p\big] - A_o T_{\perp}^p (\mathscr{X}_4 + \mathscr{X}_5\, s) \tag{16}$$

$$F_o(s) = (s - \mathscr{X}_2)\big[(s + T_M^p)(T_{\shortparallel}^p - 0{,}5 T_{\perp}^p) + 0{,}5 T_M^p T_{\perp}^p\big] + A_o T_{\perp}^p (\mathscr{X}_4 + \mathscr{X}_5\, s) \tag{17}$$

The multiplier $(s - \mathscr{X}_2)$ in the dominator is omitted as being
unessential.

As an example, some results of the АРБУС plant dynamic
property studies are to be given. As the time characteristics
of processes, run at the АРБУС plant, are calculated to be a
few tens of seconds, then the reactor thermal processes can be
considered in a quasi-static approximation. It allows to write
down the functions $F_0(s)$ and $F_I(s)$ from the equations (2)
in the form

$$F_0(s) \simeq K_e\,(s + T_e)$$
$$F_I(s) \approx K_i\,(s + T_i) \tag{18}$$

Expressions for K_e, K_i, T_i, T_e are given in Table III.

In this case the system characteristic equation will be
written down as

$$s^3 + \chi s^2 + \zeta s + B_o = 0 \tag{19}$$

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where

$$X = \frac{1}{1-f}\left\{\left[D\left(2-\frac{T^{eff}(T_1+T_2)}{T_1 T_2}(1-A_1)\right)+T_e\left(1-\frac{DT^{eff}}{T_1 T_2}(1-A_1)\right)+\right.\right.$$
$$\left.\left.+T^{eff}\left(1-A_1\frac{K_i}{K_e}\right)\right]+\left[x_3'\frac{D}{T_1}\frac{A_0 T_i^p}{K_e}\right]\right\} \qquad (20)$$

$$\zeta = \frac{1}{1-f}\left\{\left[T_e T^{eff}\left(1-A_1\frac{K_i T_i}{K_e T_e}\right)+DT^{eff}(1+A_1)\left(1-\frac{K_i}{K_e}\right)+\right.\right.$$
$$\left.+DT_e\left(2-\frac{T^{eff}(T_1+T_2)}{T_1 T_2}(1+A_1)\right)\right]+$$
$$\left.+\left[-x_3'D\frac{A_0 T_i^p}{K_e}\left(1+\frac{T^{eff}}{T_2}-\frac{T^{eff}}{T_1}\right)\right]\right\} \qquad (21)$$

$$B_0 = DT^{eff}T_e(1+A_1)\left(1-\frac{K_i T_i}{K_e T_e}\right)-x_3'DT^{eff}\frac{A_0 T_i^p}{K_e} \qquad (22)$$

Similarity factor τ_0 is determined, if B_0 in the equation (22) is equal to a unit.

Coefficients of the equation (19) and τ_0 being applicable to the АРБУС plant, are equal

$$\tau_0 \simeq 81$$
$$\zeta \simeq 3.2$$
$$X \simeq 2.6.$$

To study the roots of the characteristic equation (19), one can use diagrams (Fig.1), represented in the paper by Vyshnegradsky (2).

Notations, used in Fig.1, are as follows:

τ_s, τ_{si} - doubling period of a transient exponential component

β - dimentionless oscillation frequency of a transient periodic component

ρ - damping characteristic of oscillation amplitude of a transient periodic component.

Region I - aperiodic stability region

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Region II - oscillatory stability region

The position of a determining point with coordinates (χ, ξ), corresponding to a system dynamic parameters on Vyshnegradsky diagrams, allows to judge of the transient character in the system.

It is seen from Fig.1, that the APБУC   plant as a dynamic system is a stable low oscillatory system; a doubling period of a transient aperiodic component is

$$t_o = \frac{\tau_o \tau_s}{0,693} \simeq 140 \text{ sec};$$

an oscillatory period is

$$T = \frac{2\pi \cdot \tau_o}{\beta} \simeq 500 \text{ sec};$$

the degree of an aperiodic component damping is:

$$d = \frac{\beta \lambda_u \rho}{2\pi} \simeq |-3|$$

Time power and steam pressure change curves at a jump change in external load of 45% from nominal received on an analogue computer for a full initial non-linear system and without reactor simplifying assumptions are shown in Fig.2. It is evident from the given evaluations and curves that transients at the APБУC plant are almost aperiodic, so that practically an oscillatory component can be neglected. It means that the transient can be practically approximated to a transfer function, equivalent to an aperiodic network of a type $\left(S + \frac{0,693}{\tau_s}\right)^{-1}$, where τ_s depends on the plant parameters through the coefficients χ and ξ .

The comparison of transients investigation results on the analogue computer by using the complete non-linear system of equations with those received from Vyshnegradsky diagrams (1,2), while using the third order characteristic equation (19) has shown that this characteristic equation gives quite exact results and can be used for studies in the influence of different dynamic factors on the reactor stability.

Let us note that the dynamic coefficients D, T^{eff}, A and K_T/K_e, T_i, T_e, included in the characteristic equation coefficients (19), depend on:

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D — thermal-physical and design parameters of the secondary circuit;

A, T^{eff} — heat transfer in the steam generator and transport heat transfer along the pipings and steam generators of the primary circuit;

$\frac{K_i}{K_e}$, T_i, T_e — the reactor physical, thermal and design parameters.

It allows to investigate independently the influence of parameters of the reactor, steam generator and primary and secondary circuit coolant units on the position of the determining point at Vyshnegradsky diagram and correspondingly on the change in the plant dynamic characteristic by varing only some generalized parameters.

The influence of T^{eff}, α_T and D on the space position of the determining point of the parameters χ and ζ is shown in Fig.3.

Let us note, that the increase in T^{eff} is physically equivalent to the time decrease in the transport delay in primary circuit piping and steam generator and to improvement of the heat transfer conditions in the circuit.

It is seen from the curves in Fig.3, that the determining point shifts to an aperiodic stability region when increasing T^{eff} to about 0.15 (i.e. 10 times as high), other conditions being equal.

The influence of the reactor dynamic parameters on the stability of a closed power system, being self-regulated, can be evaluated, if the coefficients K_i/K_e, T_i, T_e are expressed in the reactivity temperature coefficient (α_T).

In Fig.3 the curve of changes in the determining point position in a phase space versus the value of α_T with constant β_T and complex $\alpha_{\gamma} T_0'$ being determined with reactor characteristics is shown. It is seen from the curve that the determining point shifts into the aperiodic stability region, the negative reactivity coefficient increasing.

If $|\alpha_T|$ decreases the curve limits the aperiodic stability region, being in the oscillatory stability region. With positive reactivity coefficient $\alpha_T > 0$ close to the fuel negative reactivity coefficient $|\beta_T|$ the dynamic closed system

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is transfered by jump into the region of absolute instability. In the same Fig. 3 the determining point position is shown versus the secondary circuit parameters, expressed in the generalized dynamic coefficient D.

Studying the curves in Fig.3, one can conclude that the change in the АРБУС type nuclear power plant parameters in a wide range does not shift it into the dynamic instability region, if the reactivity temperature coefficients remaines negative.

As with these changes the determining point is moving near the aperiodic stability region, rounding it, dimensionless time transient character is of a small change (i.e. the transients have almost an aperiodic character with the great damping decrement).

With a large negative temperature coefficient and primary circuit small transport delays the reactor system of АРБУС type tends to transfer into the region of an aperiodic stability.

On the basis of equations (20-22), table III and also of curves, in Fig.3, one can evaluate the influence of some control system parameters.

Thus, for example, coefficients $\mathcal{X}_4$, $\mathcal{X}_5$ are similar to the reactivity "temperature" coefficients α_i and α_e. Coefficients $\mathcal{X}_4$, $\mathcal{X}_5$ increasing, the determining point will tends to an aperiodic stability boundary as in case of $|\alpha_T|$ increase. The coefficient $\mathcal{X}_2$ is similar to β_0.

While choosing the optimum dynamic parameters both the character of a transient and the magnitude of asymptotic deviation of the plant process parameters are of importance, in particular, the minimum deviation of steam pressure from a nominal value at any load disturbances.

The calculations have shown that the less the asymptotic pressure value (S → 0), the plant operating under self-regulation conditions, the better the steam generator heat transfer conditions (KF) and this value depends on the initial pressure value:

$$\Delta P_\infty = -\frac{(A_3 + A_5)\left(1 + \frac{\alpha_i}{\alpha_e} A_1\right)}{D(1 + A_1)\left(1 + \frac{\alpha_i}{\alpha_e}\right)} \Delta W_T \simeq -\frac{r + \Delta i'}{\left(\frac{\partial T_s}{\partial p}\right)_{P_0} KF} \Delta W_T \quad (23)$$

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For the АРБУС plant under self-regulation conditions of operation the relative pressure change is equal to about 25% of (i.e. about 6 atm.) while tripping out the full external load , which amounts to about 60% of full power.

While taking into account transient character being close to aperiodic and pressure deviation from the nominal, it is possible to say, that the АРБУС plant can be in stable operation under self-regulation conditions (without AP), at least, under conditions when external load changes do not exceed 30% of the full power.

Pressure deviation from the nominal value $(\Delta P\infty)$ for the given type of a steam generator can be reduced by making corrections for pressure in automatic power regulator reading and by selecting corresponding parameters x_2 and x_3, x_4 . Then $\Delta P\infty$ will be equal

$$\Delta P\infty = - \frac{(A_3 + A_5)\left[(1-A_1)-(1+A_1)\alpha_P \frac{x_4}{x_2}\right]}{D(1+A_1)\alpha_P \left(\frac{x_4}{x_2} + \frac{1}{\psi}\frac{x_3}{x_2}\right)} \Delta W_T .$$

In case of the АРБУС plant pressure correction allows to reduce relative pressure change at trippingout 60% of full power to about 12% P_0 (i.e. to $\Delta P\infty \cong 3$ atm).

However, at large ratios x_3/x_2 transients quality becomes slightly worse, their oscillations being increased. Indeed, increasing $|x_3|$ χ is decreased, and γ being increased, this is equivalent to the oscillation frequency increase and to the decrease in oscillation damping degree.

The theoretical results of dynamic properties investigations according to the methods described were verified in the course of preliminary experimental studies at the АРБУС plant start-up and test operations (3). Experimental and design curves of power and pressure variations with 24% external electric load removing are compared in Fig.4.

Due to correction for pressure change in the setter of an automatic power regulator stable operation of the АРБУС plant can be provided at full external load removing and increase. Then, steam pressure deviation from the nominal value will not exceed 2.5 atm.

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Table I

Nomenclature

τ_o – time scale

λ – radioactive decay constant of the delayed neutron emitter

ρ – reactivity

ρ_{rod} – control rods reactivity

α_T – coolant reactivity temperature coefficient

β_T – fuel reactivity temperature coefficient

C – specific heat

M – mass

KF – total heat flow per unit of temperature drop

G – primary circuit coolant flow rate

W_{turb} – turbine steam flow rate

N_o – nominal reactor power

$\bar{\theta}_o$ – nominal average reactor coolant temperature

$\gamma'\gamma''$ – saturation water and steam densities, respectively

r – steam generation specific heat

i' – saturation water enthalpy

i_{sw} – reactor input water enthalpy

V_{steam} – secondary circuit steam volume

V_{water} – secondary circuit boiling water volume

$T_{satur.}$ – saturation water temperature

x_i – automatic control system coefficients

τ_1, τ_2 – transfer time delay in pipings from the reactor to the steam generator and in the opposite direction, respectively

n – relative reactor power change

C – delayed neutron emitters relative concentration change

$\vartheta_{in}, \vartheta_{out}$ – primary circuit coolant relative temperature change at the reactor inlet and outlet, respectively

ϑ_1, ϑ_2 – primary circuit coolant relative temperature change at the steam generator inlet and outlet, respectively

u – fuel elements relative average temperature change

P – secondary circuit steam relative pressure change.

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Symbols

ρ - coefficient applied to the reactor

Sg - coefficient applied to the steam generator

o - it denotes that a given value corresponds to plant parameters initial values.

Table 2.

Plant dynamic parameters

$$T_i = \frac{\tau_0}{\tau_i} \qquad \tau_M, \tau_\perp = \left[\frac{CM}{KF}\right]$$

$$\tau_{||}, \tau_{|}, \tau_2 = \left[\frac{M}{P}\right]$$

$$\tau_0 = \lambda^{-1}$$

$$A_0 = \frac{N_0 \tau_0}{(CM)_M^P \bar{\theta}_0} \qquad\qquad T^{sg} = T_s^{sg} + 0.5\, T_\perp^{sg}$$

$$A_1 = \frac{T_s^{sg} - 0.5\, T_\perp^{sg}}{T^{sg}} \qquad T_w = \frac{W_{T_0}\, \tau_0}{P_0 \left(\frac{\partial \gamma''}{\partial P}\right)_0 V_{\text{steam}}}$$

$$A_2 = 1 - A_1 \qquad\qquad T_{S_0} = \frac{KF \bar{\theta}_0\, \tau_0}{P\left(\frac{\partial \gamma''}{\partial P}\right) V_{\text{steam}}}$$

$$A_3 = \frac{i' - i_{sw}}{r}\, \frac{T_w}{\left(1 + x\frac{V_{\text{steam}}}{V_{\text{water}}}\right)} \qquad D = \Psi A_4$$

$$\Psi = \left(\frac{\partial T_s}{\partial P}\right)_0 \frac{P_0}{\bar{\theta}_0}$$

$$A_4 = \frac{0.5\, T_{S_0}}{1 + x\frac{V_{\text{steam}}}{V_{\text{water}}}}$$

$$A_5 = \frac{T_w}{1 + x\frac{V_{\text{steam}}}{V_{\text{water}}}} \qquad x = \left(\frac{\partial i' \gamma'}{\partial P}\right)_0 \Big/ r\left(\frac{\partial \gamma''}{\partial P}\right)_0$$

$$\alpha_\rho = \frac{A_0\, T_\perp^P}{T_M^P\, T_{||}^P} \qquad\qquad f = \frac{D A_2\, T^{eff}}{T_1\, T_2}$$

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Table 3. __Reactor effective dynamic parameters__

With the automatic control system	Self-regulation

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$$K_i = T_m^P T_{II}^P \left\{ 1 - \mathscr{x}_2 \frac{T_{II}^P - 0.5 T_I^P}{T_m^P T_{II}^P} - \mathscr{x}_5 d_\rho \right\} \qquad K_i = T_m^P T_{II}^P \left\{ 1 + d_i d_\rho \right\}$$

$$K_e = T_m^P T_{II}^P \left\{ 1 - \mathscr{x}_2 \frac{T_m^P + 0.5 T_I^P + T_{II}^P}{T_m^P T_{II}^P} - \mathscr{x}_5 d_\rho \right\} \qquad K_e = T_m^P T_{II}^P \left\{ 1 - (d_e + \beta_0 T_0) d_\rho \right\}$$

$$T_i = - \frac{\mathscr{x}_2 + \mathscr{x}_4 d_\rho}{1 - \mathscr{x}_2 \dfrac{T_{II}^P - 0.5 T_I}{T_m^P T_{II}^P} - \mathscr{x}_5 d_\rho} \qquad T_i = \frac{d_i d_\rho T_0}{1 + d_i d_\rho}$$

$$T_e = \frac{\mathscr{x}_2 + \mathscr{x}_4 d_\rho}{1 - \mathscr{x}_2 \dfrac{T_m^P + T_{II}^P + 0.5 T_I^P}{T_m^P T_{II}^P} - \mathscr{x}_5 d_\rho} \qquad T_e = - \frac{d_e d_\rho T_0}{1 - d_i d_\rho}$$

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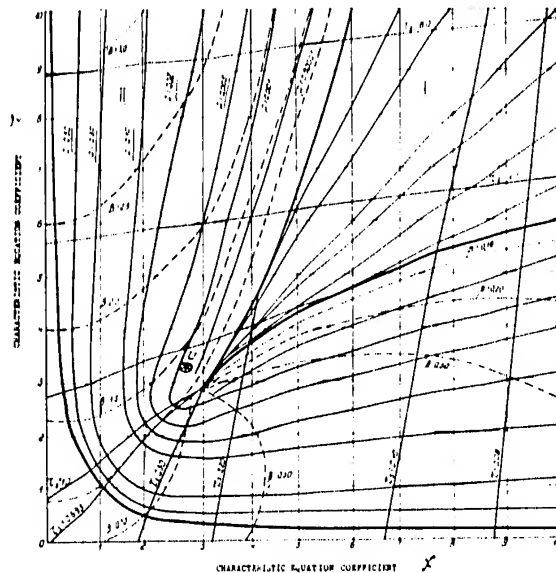   ference on Peaceful use of Atomic Energy.

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Fig.1. Transient parameters diagram in the third order
dynamic systems.
I - aperiodic stability region
II - oscillatory stability region
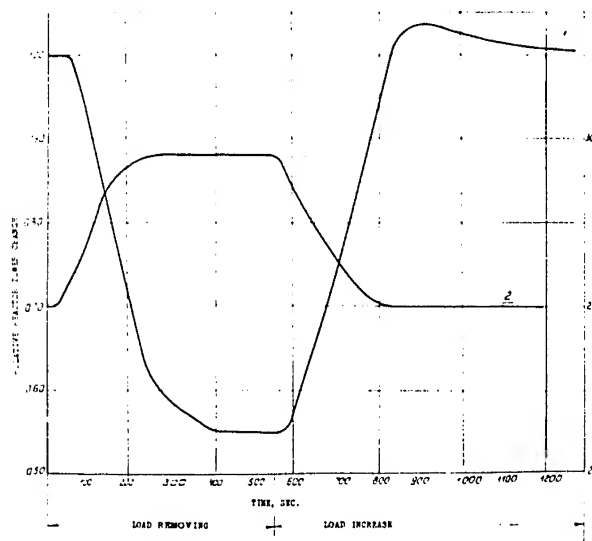The point U corresponds to the АРБУС
plant parameters.

Fig.2. Reactor power and steam pressure changes at load
removing and subsequent 45% increase of it.
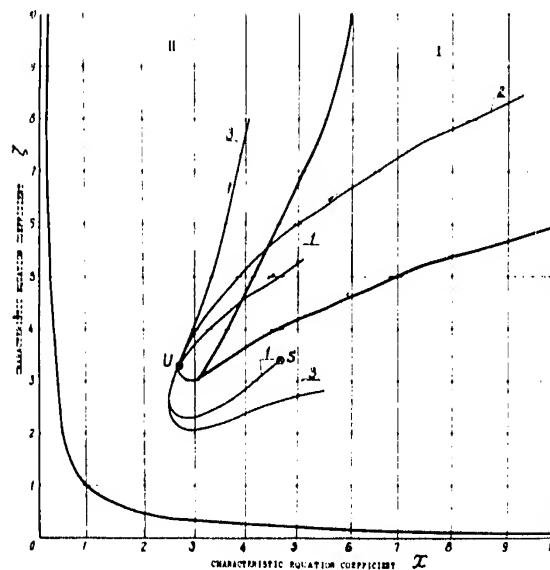1 - Relative reactor power. 2 - Steam pressure.

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Fig.3. Determining point path versus the parameters change of the
АРБУС plant at the self-regulation mode of operation. The
arrows direction on curves corresponds to parameters in-
crease:

Curve (1) α_T from $-\infty$ to $+0.001$
-"- (2) T_{eff} from $0.5 \cdot 10^{-2}$ to 0.5
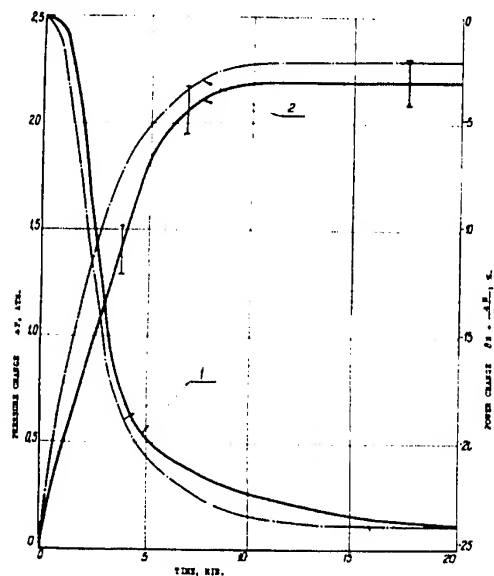-"- (3) D from $0.5 \cdot 10^{-3}$ to 0.10

Fig.4. Power and pressure change at load removing
—·—— - designed curve
———— - experimental curve
1. Power, %. 2. Pressure, atm.

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